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14. ABSTRACT
In January 2001, the X-50LR program was initiated to scale the Lightcraft concept ultimately to a 50-cm focal diameter, and to launch a 50 cm, fully functional vehicle, into space in either a sounding rocket or suborbital trajectory by the end of FY 2009. The current work involves scaling from a 10-cm aluminum Lightcraft to a composite 25-cm laser ramjet vehicle (X-25LR). An overview and status of this program will be given in terms of the various efforts that support this development. These efforts will include testing at the High Energy Laser System Test Facility (HELSTF), New Mexico; some results of the laser launch system study by Flight Unlimited; the development of silicon carbide materials for X-25LR parabolic reflectors by Trex Enterprises; supporting research by Air Force Office of Scientific Research (AFOSR); the different facets of attitude control in a small business program with Polaris Sensors Technology; continuing development of a launch model at The Pennsylvania State University; and, the development of a thrust measurement technique, and the use of a "mini-thruster" for research with The University of Alabama, Huntsville, in collaboration with the AFRL. This paper will be followed by a number of papers giving additional details of the efforts briefly overviewed in this presentation.

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An Overview of the Experimental 50-cm Laser Ramjet (X-50LR) Program

The 4th International Symposium on Beamed Energy Propulsion

15-18 *November 2005*

Nara, Japan

Dr. Franklin B. Mead, Jr.,

Dr. C. William Larson, and

Mr. Sean D. Knecht

Propulsion Directorate

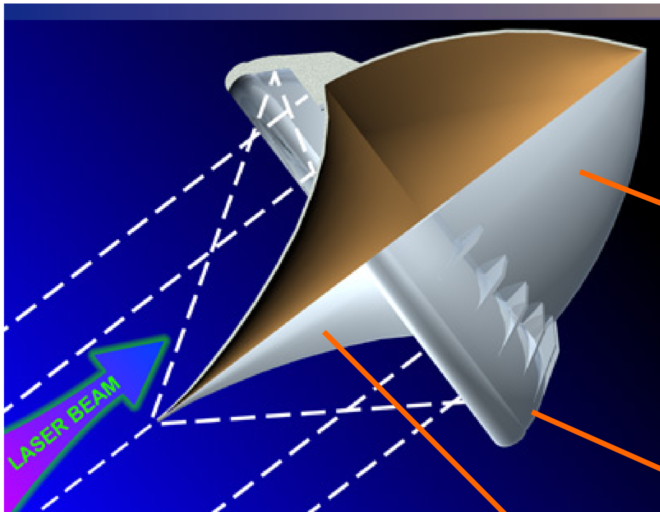
Air Force Research Laboratory

Edwards Air Force Base, CA

Presentation Outline

- The Lightcraft Concept
- The Experimental 50-cm Laser Ramjet (X-50LR) Program
  - Objectives, Critical Technologies, and Payoffs
  - Current Program Collaborations And Technical Contributions
    - Testing at HELSTF
      - X-25LR
      - 10-cm Lightcraft
      - Mini-thruster research
    - AFOSR Programs and Support
      - High I_{sp} Propellants
    - Attitude Control (Phase II SBIR)
      - Thermal Structural Analysis of Parabolic Plug Nozzle
      - Adjustable Pivot Point Pendulum
    - Some Launch Code Results
- Summary

The Lightcraft Concept



Recent AFRL Test Vehicle

- A Lightcraft is a small spacecraft; diameter is ≤1.0 m, weight is ≤ 8.0 kg (≤2.0 kg payload)

Forebody

- ➢ Aerodynamically contoured surface
- ➢ Analogous to rocket payload bay; opens in space to release payload and expose solar cells

Shroud

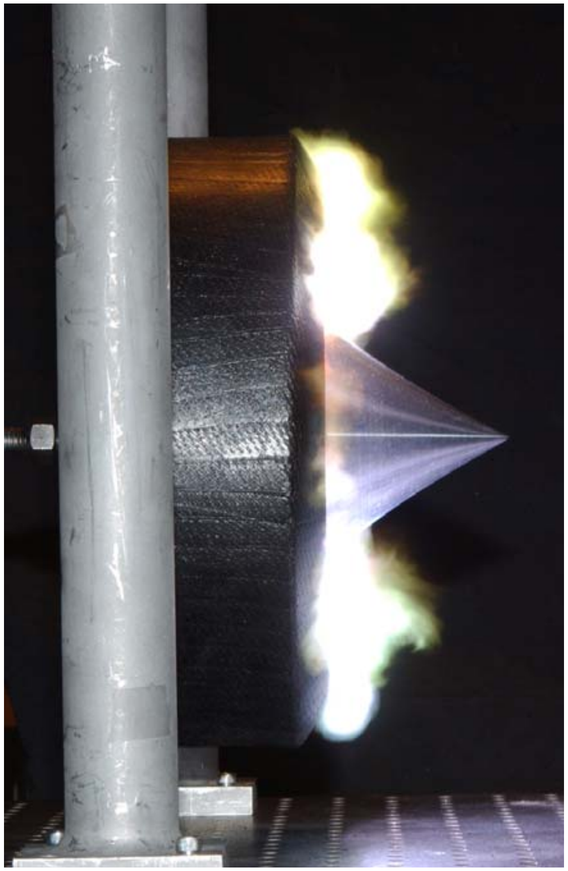
- ➢ Centrally located "belt"
- ➢ Analogous to rocket combustion chamber; ejected plasma provides thrust

Afterbody

- ➢ Analogous to rocket nozzle; parabolic mirror and plug nozzle

AFRL/PRS Program For Laser Propulsion Development

- Objectives
  - Eliminate remaining major technical hurdles for a laser launch vehicle
    - Critical Technologies
      - Airframe & Structure - Materials
      - Ablative energetic propellants
      - Theoretical modeling and flight simulation
      - Electronic Systems
      - Chemical Propulsion
  - Conduct a high altitude flight demonstration using the technology developed under this program
    - Using PLVTS CO_2 laser upgraded in power by factor of 2 or 3
- Payoffs
  - Provide a paradigm shift for space access
    - Entirely different infrastructure
      - No huge motorized tractors for moving vehicles
      - No skyscraper gantries
      - No standing army of mechanics & technicians
      - No toxic fuels
      - No significant explosive hazards
      - No large propellant farms
  - Low cost access to space for nano-satellites



25 cm Laboratory Model

Current Program Collaborations

Mini-Thruster Research
U. Alabama, Huntsville
Dr. Andrew Pakhomov

CO2 Laser: Lab & Flight Testing
HELSTF/WSMR
Mr. Steve Squires

Computer Launch Model
U. Washington (Co-Op)
Mr. Sean Knecht

X – 50LR
Dr. Franklin Mead, Jr.
AFRL/PRSP

Attitude Control
Polaris Sensors Techn.
Mr. John Harchanko

Ablation of Liquid Fuels
Tokyo Inst. of Technology
Dr. Shigeaki Uchida

Laser Launchers
AFOSR MURI/SBIR/STTR
Dr. Mitat Birkan

Ablation of Solid Fuels
Inst. of Technical Phys.
Mr. Wolfgang Schall

= Government Agencies
= Contractors
= Foreign Research

Pulsed Laser Vulnerability Test System (PLVTS)

Original Performance

- 1,000 joules/pulse
- 10 Hz
- 30 µsec pulses

Modified Performance

- 1998
  - 400 joules/pulse
  - 25 Hz
  - 18 µsec pulses
- 1999
  - 150 joules/pulse
  - 30 Hz
  - 5 µsec pulses

The PLVTS has powered the AFRL laser propulsion test and evaluation program

Proposed Performance

- 1,500 joules/pulse
- 20 to 35 Hz
- 25 µs pulses

Team December 2004

Pulsed Laser Vulnerability Test System

Frank Mead, Bill Larson, Sean Knecht, AFRL/PRSP
Jim Shryne, RSI (Photographer)
John Harchanko, POLARIS TECHNOLOGIES
Steve Squires, Chris Beairsto, Mike Thurston, &
Jay Spray, WSMR/HELSTF/PLVTS

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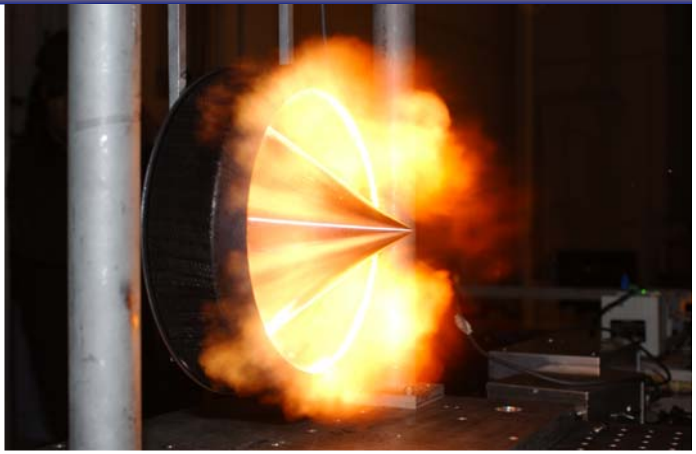
Mettler Balance or Digital Balance

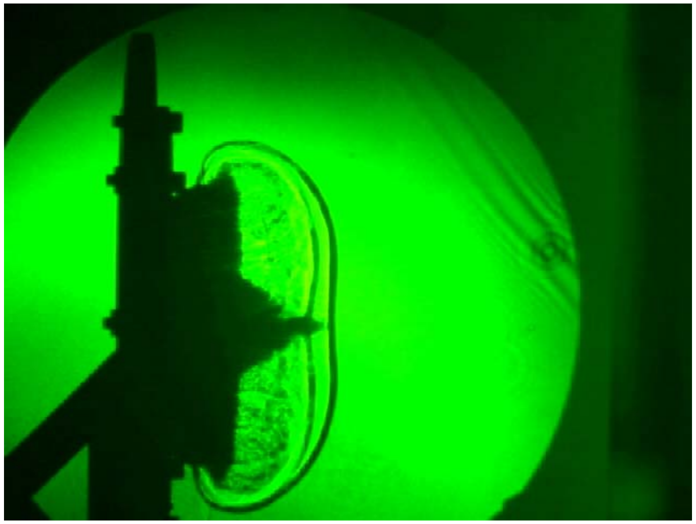
Measure mass to $\pm$ 0.3 mg

Laboratory Tests at HELSTF

- ***X-25LR Bench Model***
  - Fabricated by COI Ceramics
    - Amorphous SiNC Matrix
    - Reinforced with Nicalon fiber
    - Recommended up to 1473º K
  - Tested With Delrin®
    - COI Nicalon parabolas gave poor performance
      - Fibers coated with Cu yielded poor, inaccurate mirror quality
    - Required Al parabola with mirror finish
      - Performance Excellent
- **Shadowgraph Tests in Air**
  - 10-cm Aluminum Lightcraft Laboratory Model
  - 18 μs and 300 J
  - Exit plane traverse = 10 μs



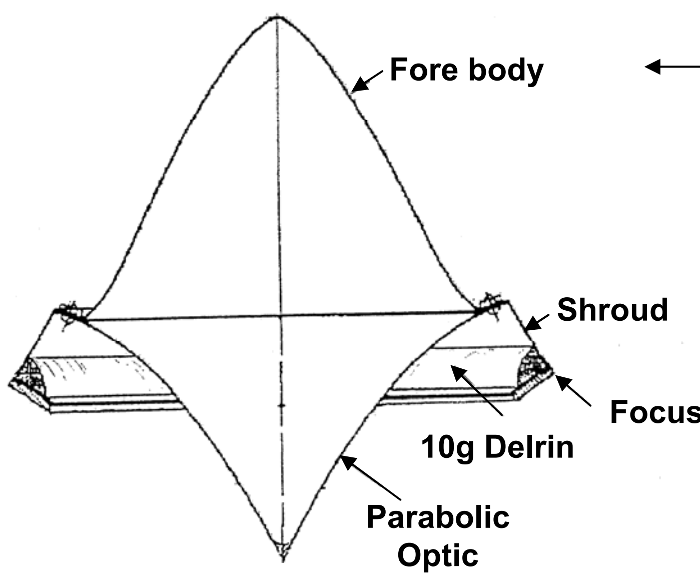
X-25LR Test with Black Delrin®



10-cm Lightcraft Shadowgraph Test at 45 μs

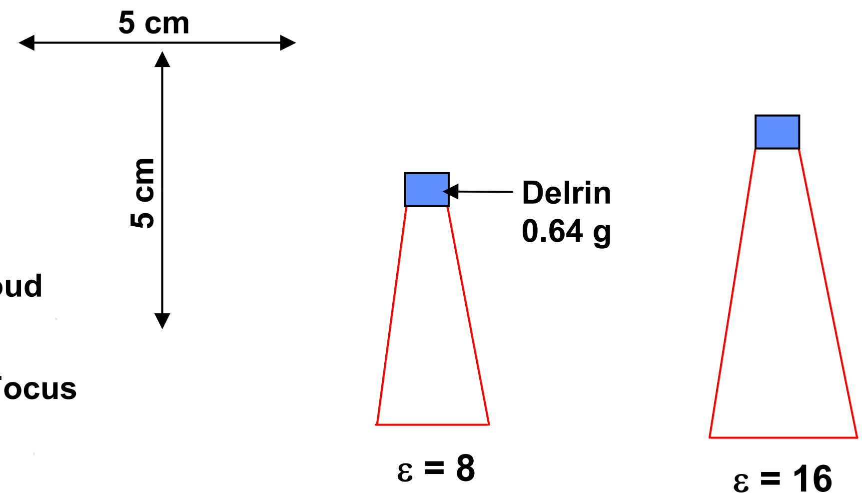
Lightcraft and Mini-Nozzle Standard

200-3/4 Lightcraft (10-cm)



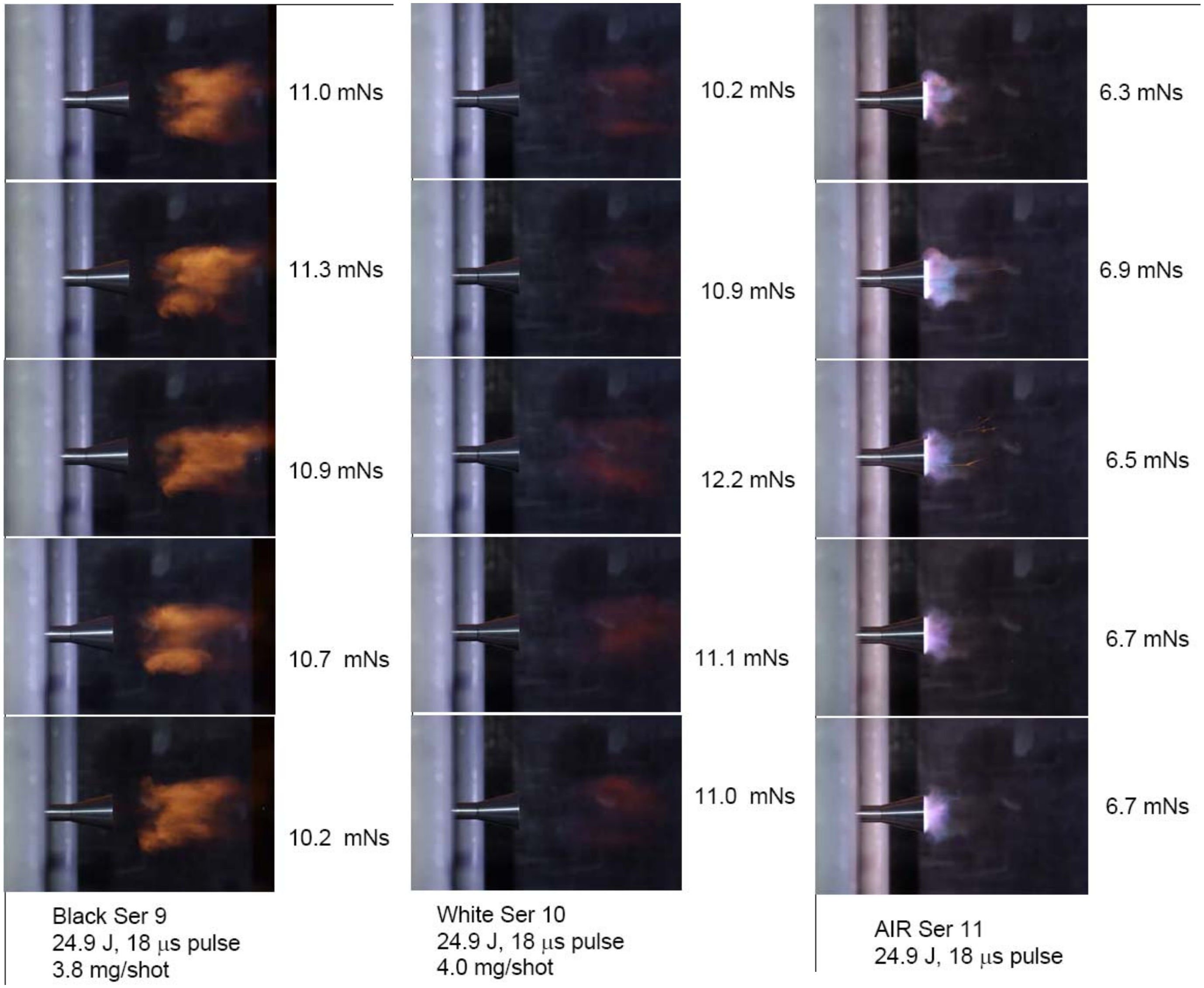
ε (ideal plug nozzle) = 14
M = 40g
Delrin surface area ~ 25 cm^2
350 J/25 cm^2/18 μs = 0.8 MW/cm^2
Cm = 450 N/MW, E_L/m = 5.1 MJ/kg
V_e = 2270 m/s, efficiency = 0.51
T/W = Cm·P/mg = 11 at P=10 kW

Mini-Thruster
26^o divergence angle

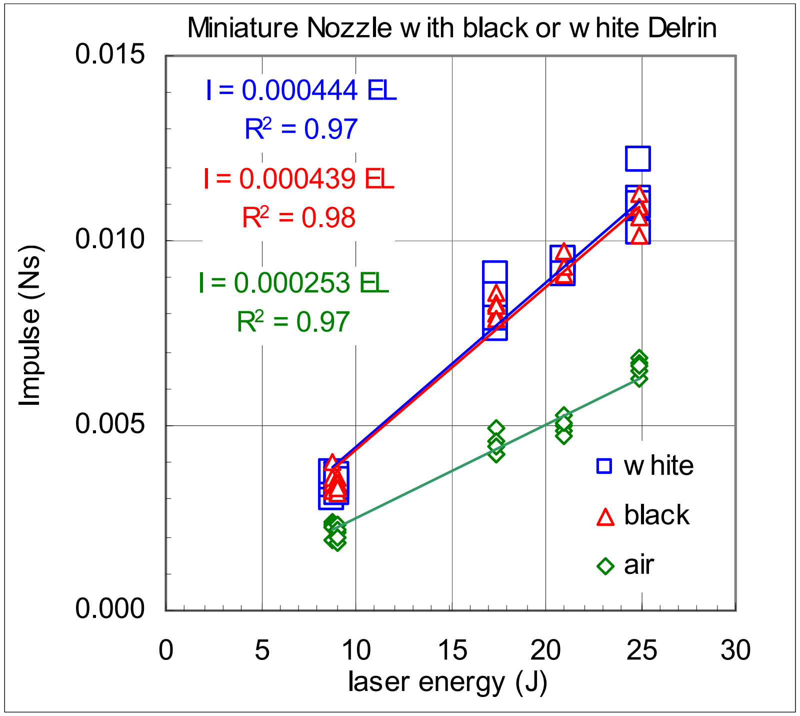


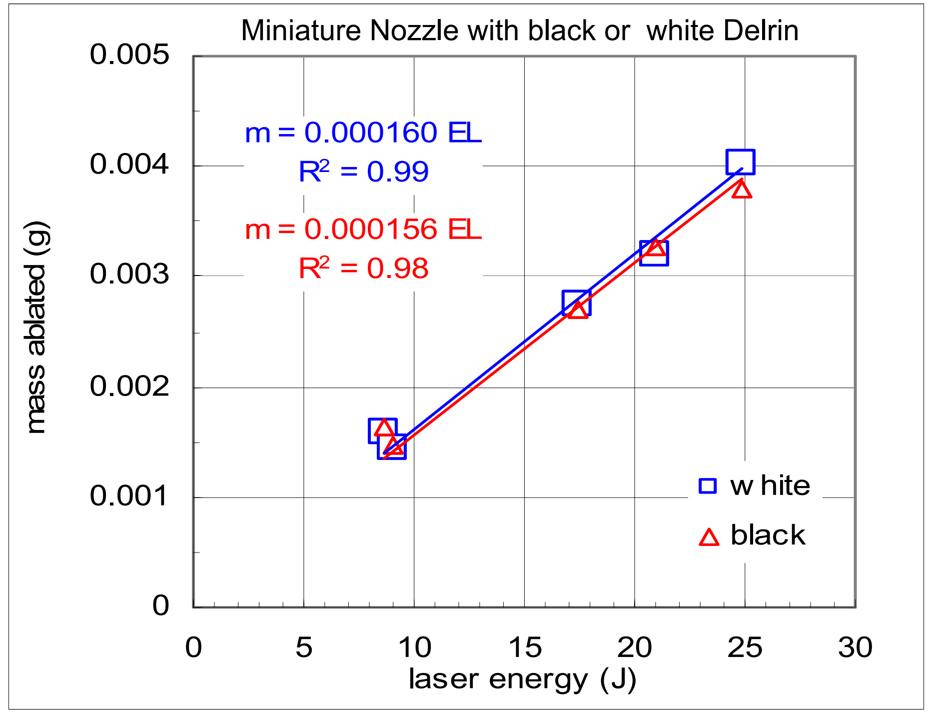
ε = 8
M = 7.8 g
Delrin surface area ~ 0.71 cm^2
25 J/0.71 cm^2/18 μs = 2.0 MW/cm^2
Cm = 442 N/MW, EL/m = 6.3 MJ/kg
V_e = 2795, efficiency = 0.62

Mini-Thruster 25 J, 18 μs, 0.71 cm^2



I, m, E_L for Mini-Thruster





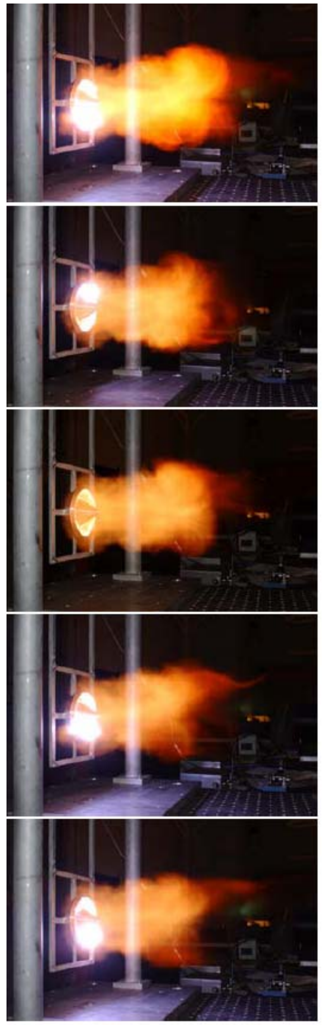
I/E_L = 444 Ns/MJ **m/E_L = 0.160 mg/J**

$V_e = (I/E_L)/(m/E_L)$ = 2775 m/s = 283 s of I_{sp}

Efficiency = $\frac{1}{2}(I/E_L)^2/(m/E_L) = 0.616 = \alpha\beta\Phi$*

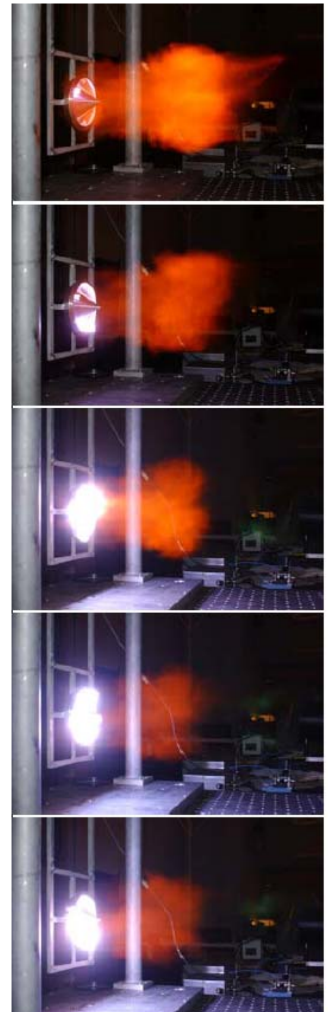
*** See: Larson et al., AIAA 2002-0632, 2002**

10 cm Light Craft 322 J, 18 μs



139.2 mNs
144.8 mNs
153.9 mNs
146.7 mNs
150.2 mNs

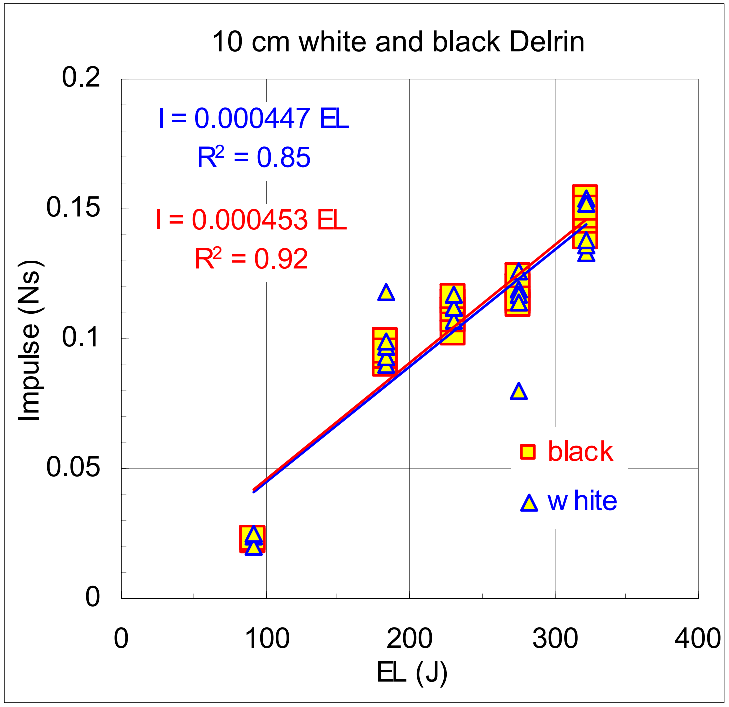
Black Ser 7
322 J
59.8 mg/shot

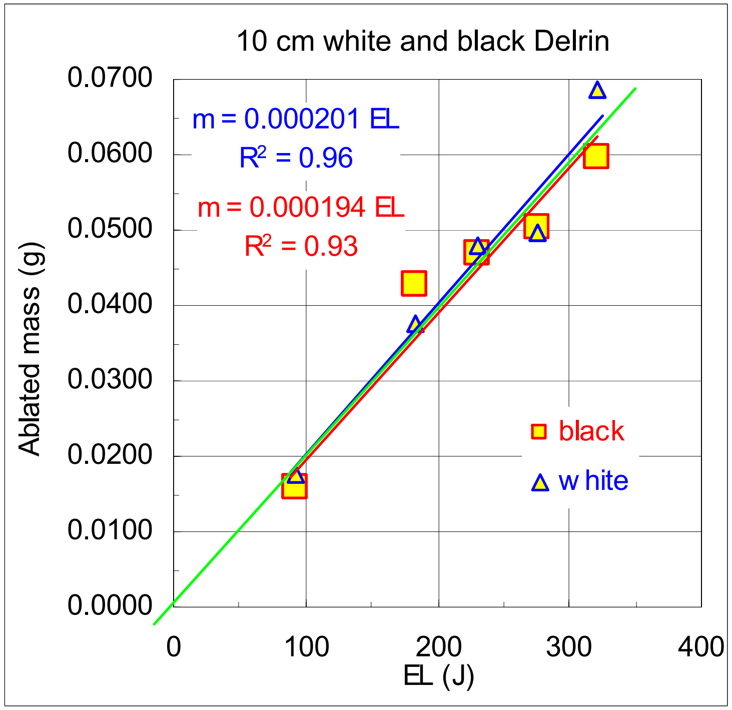


154.1mNs
151.8 mNs
133.0 mNs
136.1 mNs
137.8 mNs

White Ser 6
322 J
68.7 mg/shot

I, m, E_L for Lightcraft 200-3/4 (10-cm)





I/E_L = 447 Ns/MJ **m/E_L = 0.201 mg/J**

$V_e = (I/E_L)/(m/E_L) = 2224$ m/s

Efficiency = $\frac{1}{2}(I/E_L)^2/(m/E_L) = 0.497 = \alpha\beta\Phi$

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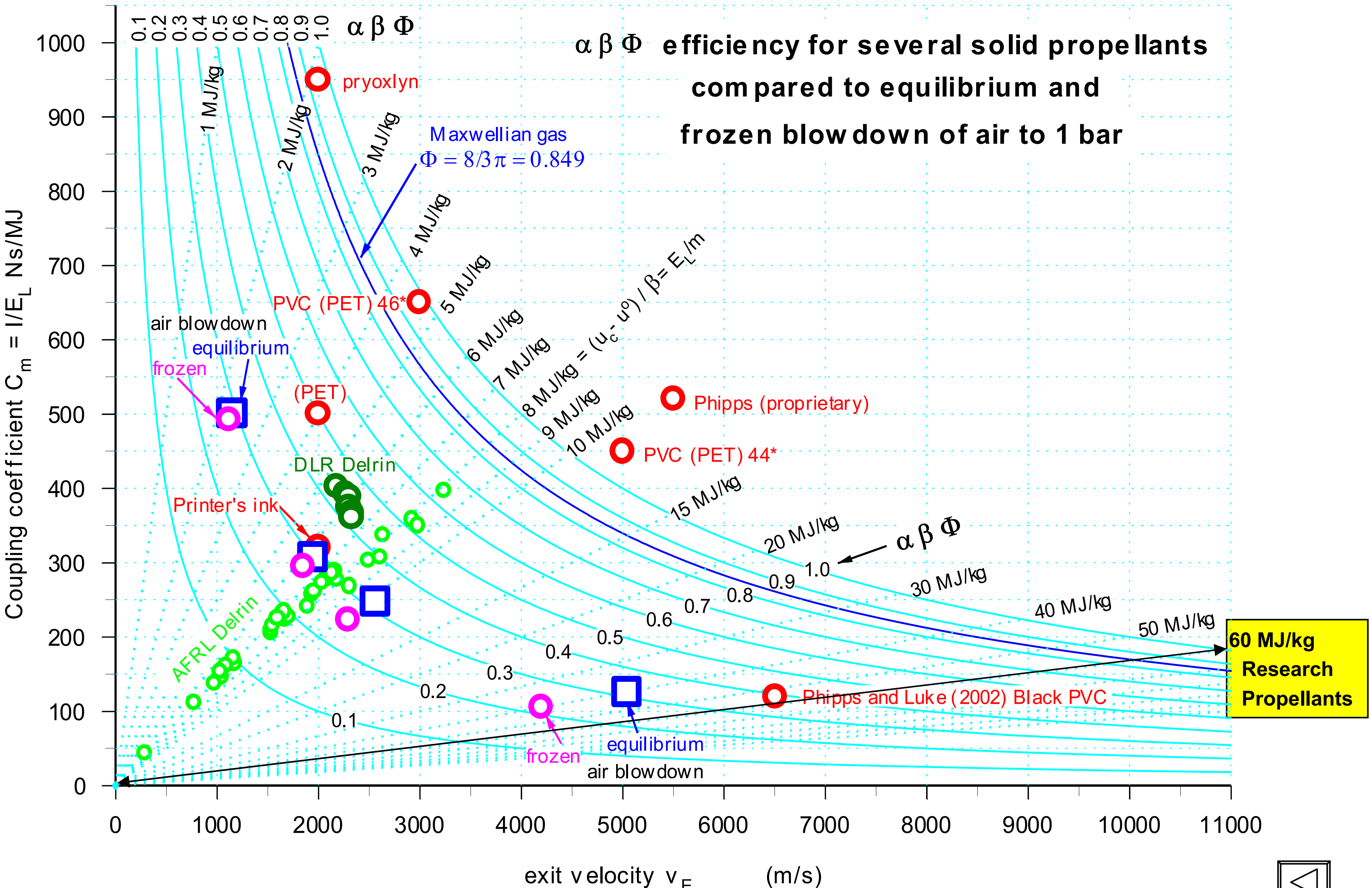
Conclusions/Work in Progress

- C_m= 450 N/MW for Lightcraft with Delrin® (350 J, 18 μs)
- C_m= 442 N/MW for mini-thruster with Delrin® (25 J, 18 μs)
- 51 % efficiency for E_L to jet KE for Lightcraft
- 62 % efficiency for E_L to jet KE for mini-thruster
- Future experiments
  - Vary pulse width, 5 and 30 μs, expansion ratio, ε = 4, 16, …
  - Increase E_L up to ~ 100 J/pulse in mini-thruster
  - Measure time resolved thrust with piezoelectric sensor
  - Develop chemically enhanced ablative propellants
- Future calculations with chemical equilibrium applications code
  - Factor pressure thrust into analysis
  - Analyze chemically energetic propellants*

Performance Map of Known Laser Propellants



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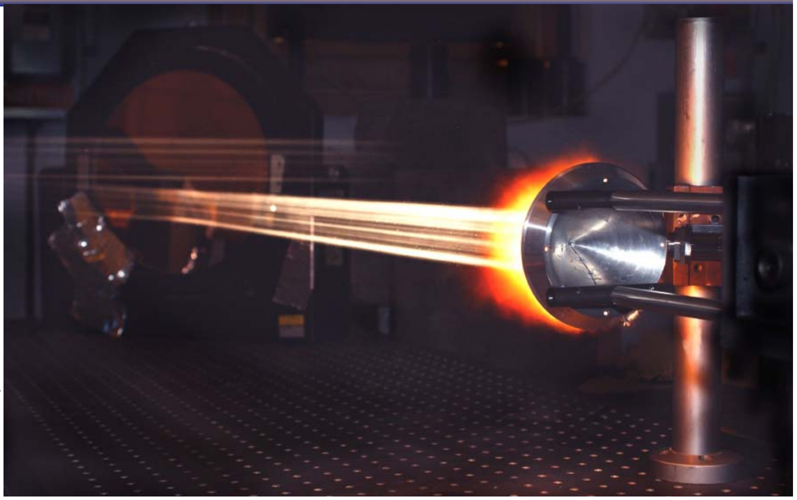
Thermal Structural Analysis
(Laser Lightcraft Thin-Walled Aluminum Plug Nozzle)

- **Performed by SYColman**
  - ➢ **Directed by Polaris Sensor Technologies**
    - **Under SBIR Phase II contract for attitude control**
- **Desire to predict deformed shape of parabola as a function of time and input power**
  - ➢ **Based on initial geometry and varying temperature**
- **Results from model**
  - ➢ **Maximum displacement increases linearly with temperature**
  - ➢ **Significant optical degradation and distortion of reflected beam with predicted beam surface deformations**
  - ➢ **COI Nicalon material showed little or no resultant deformation ≤ 1,000º F**



Full Power, Multi-Pulse Laser Heating of Flight-weight Lightcraft Parabola with Shroud Attached

Impulse Pendulum with Adjustable Pivot Point

- **Improved technique**
  - ➢ **Pendulum is brought into balance by adjusting its pivot-point**
    - ▪ **Coincide with Lightcraft/pendulum's combined center of gravity**
  - ➢ **More sensitive than standard pendulum**
  - ➢ **Developed for measuring side/restoring forces**
  - ➢ **Gantry size determines range of test articles that can be handled***

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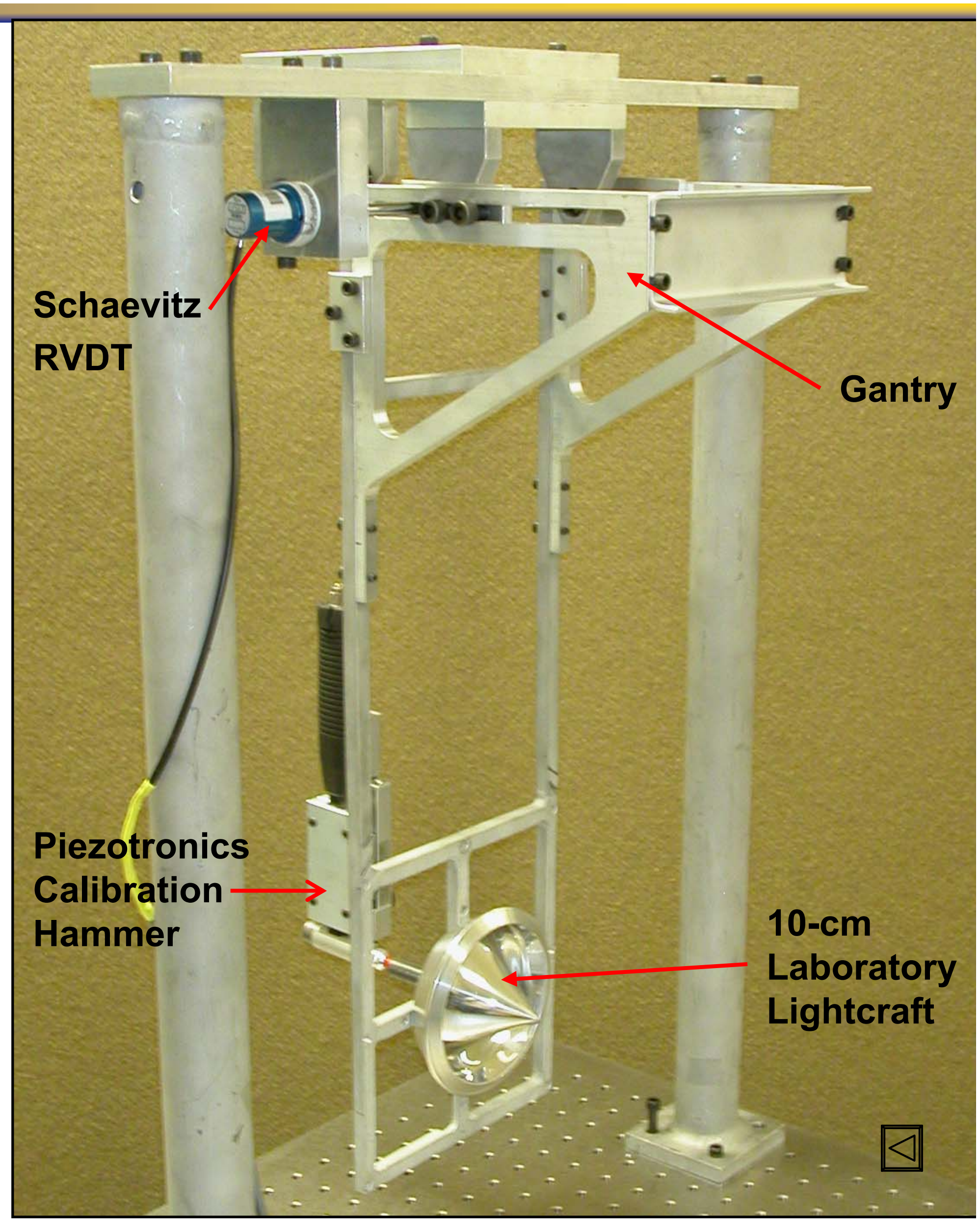
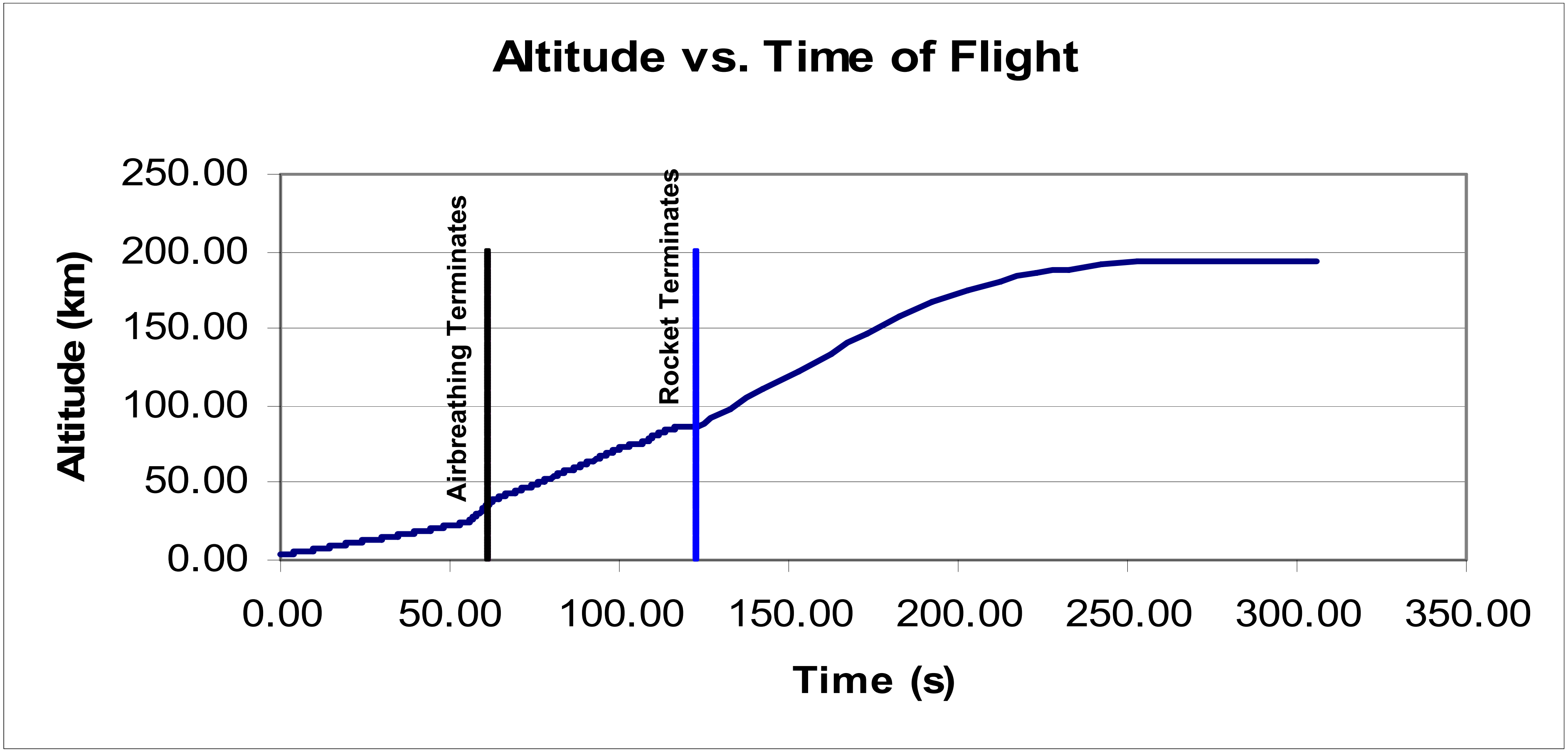


X-25LR Space Launch Simulation

- **Pulsed CO_2 laser**
  - **1 MW**
  - **1,000 joules/pulse**
  - **30 Hz**
  - **25 μs pulses**

- **Vehicle parameters for simulations**
  - **25 cm diameter,**
  - **Dry mass (structure) = 0.21 kg**
  - **Payload = 0.21 kg**
  - **Propellant (mass fraction = ½) = 0.42 kg**
  - **Total mass = 0.84 kg (1.85 lbs)**

Results: 1 MW 10.6 μm Laser



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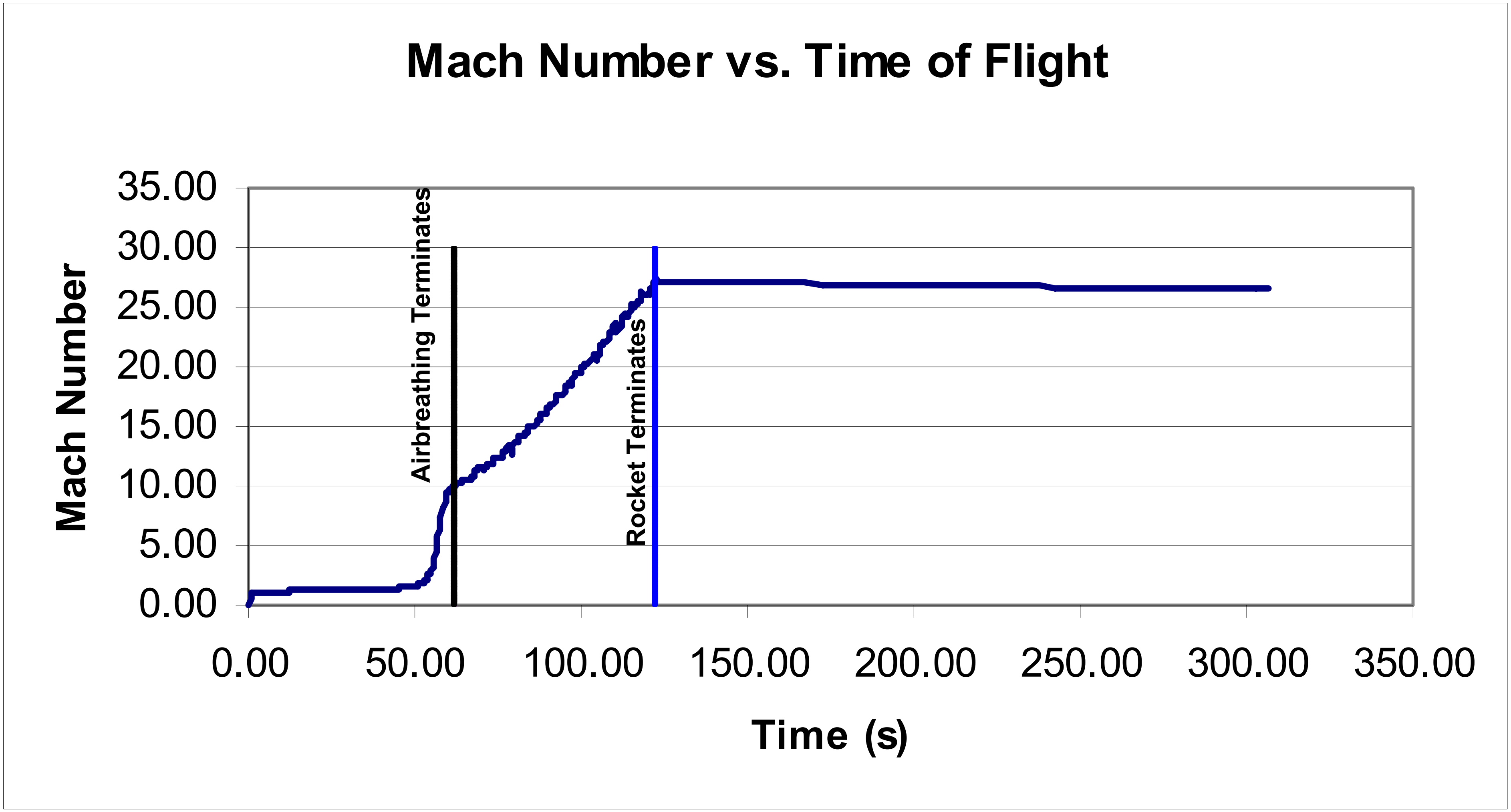
Results: 1 MW 10.6 μm Laser



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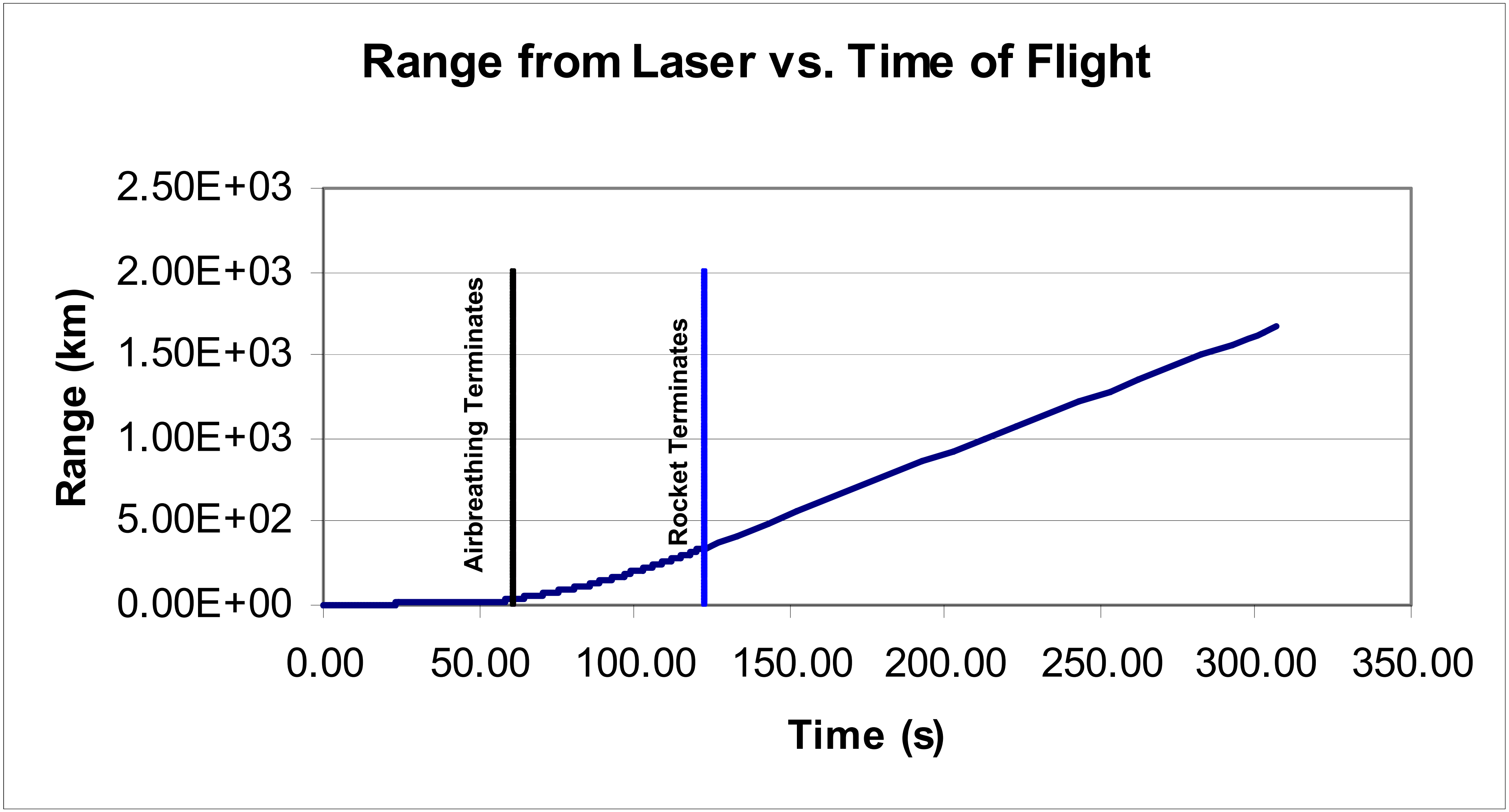

X-50LR Program Summary

- **AFRL laser propulsion ready for advanced development (6.3) with a quarter scale vehicle**
  - ➢ **Composite, airbreathing, 25-cm vehicle needs additional development**
  - ➢ **High altitude flights are possible using active ACS on a 25-cm laser propelled vehicle**
- **Critical technologies required to be ready for engineering development (6.4)**
  - ➢ ***Airframe & Structure – Materials***
  - ➢ ***Ablative energetic propellants***
  - ➢ ***Theoretical modeling and flight simulation***
  - ➢ ***Guidance, Control, Power, & Sensors***
  - ➢ ***Chemical Propulsion***
- **Operational status could be reached within 3 to 4 years**
  - ➢ **A MW class laser will be required**
  - ➢ **The major technologies required for laser propulsion will need to be demonstrated under an advanced development program**
- **A rather modest investment to achieve a means for a new, unique, low-cost access to space**

Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future

The End

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